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ASCA GUEST INVESTIGATOR PROGRAM

FINAL TECHNICAL REPORT FOR NAG 5-2556

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Final Technical Report for NAG 5-2556

David J. Helfand, Principal Investigator

This recently expired grant has supported the work of the PI, his students, and his collaborators on a variety of ASCA projects over the past four years. Annual reports have summarized much of the work accomplished; here we provide a brief review of the work resulting from this effort, and a summary of the personnel who have benefited from the grant's support.

Starburst Galaxies with Extreme X-ray Luminosities

This project began as a careful examination of the claims of Boller et al. (1992) that there were dozens of “normal” galaxies in the *ROSAT* All-Sky Survey that had X-ray luminosities in excess of 10^{42} erg s⁻¹, higher than that seen in the hundreds of non-AGN galaxies observed with *Einstein*. If true, this suggested that X-ray emission associated with star formation activity might have a significant contribution to make to the still unexplained cosmic X-ray background (XRB). Since some of our earlier work with the *Einstein* Observatory Deep Surveys had suggested a similar possibility and several sets of authors over the years had modelled the starburst XRB contribution, these claims were worth pursuing. Our work expanded the examination beyond the RASS to include earlier claims of high-luminosity galaxies powered by starburst emission (selected in this case on the basis of the far-IR luminosities).

The result of extensive followup observations under several programs using *ROSAT*, *ASCA*, and ground-based facilities was to show that nearly all of these objects in fact have hidden AGN at their cores, and that their luminosities are not in any way extraordinary. These results were published in several papers including:

Moran, E.C., Halpern, J.P., and Helfand, D.J. 1996, “Classification of *IRAS*-Selected X-ray Galaxies in the *ROSAT* All-Sky Survey,” *Ap.J.*, **461**, 127.

Halpern, J.P., Helfand, D.J., and Moran, E.C. 1995, “No X-ray Luminous Starbursts in the *Einstein* Medium Sensitivity Survey, Either,” *Ap.J.*, **453**, 611.

One of our more recent *ASCA* observations of a putative X-ray luminous starburst, *IRAS* 00317-2142, is exemplary of both the work and the results that have characterized our followup program. In the *ROSAT* All-Sky Survey, the reported luminosity of *IRAS*

00317-2142 is $\sim 10^{43}$ ergs s $^{-1}$, typical for a broad-line Seyfert galaxy. However, at all other wavelengths, the characteristics of this object are dominated by the signatures of a nuclear star-forming region, which are normally 2-3 orders of magnitude fainter in the X-ray band. At 1.4 GHz, the emission from the galaxy is amorphous, extending over several kiloparsecs. In fact, 94% of the 20 cm flux is associated with extended, steep-spectrum emission from the starburst. Only at 8.4 GHz is the faint, unresolved AGN core unambiguously revealed. The optical emission-line flux ratios are also suggestive of vigorous star formation in IRAS 00317-2142. Broad [O III] lines and weak, broad wings on the H alpha line provide subtle indications of the presence of a Seyfert nucleus. Similarly, the UV spectrum of the galaxy possesses absorption features associated with very young, hot stars, as well as a strong Lyman alpha emission line, suggesting once more composite starburst/Seyfert activity.

To reconcile the high soft X-ray luminosity of IRAS 00317-2142 with its properties at other wavelengths, we observed the galaxy with *ASCA* for 37 ks with the SIS and 41 ks with the GIS. In combination with an archived 9.3 ks *ROSAT* PSPC observation, obtained earlier, these data reveal significant spectral and flux variability, which indicate unambiguously that the AGN dominates in the X-ray band. Both the PSPC and *ASCA* spectra are adequately fitted with simple absorbed power-law models. The measured power-law photon index in the PSPC spectrum is 2.46 ± 0.20 (90% conf.), from which we derive a 0.5-2.4 keV flux of 1.8×10^{-12} ergs cm $^{-2}$ s $^{-1}$. In the *ASCA* spectrum, $\Gamma = 1.88 \pm 0.08$, with a 0.5-2 keV flux of 5.0×10^{-13} ergs cm $^{-2}$ s $^{-1}$. The soft X-ray flux dropped by a factor of 3.6 over a three-and-a-half year span. The PSPC light curve indicates $\sim 30\%$ variability on the timescale of a day.

So why is the AGN in IRAS 00317-2142 so inconspicuous at other wavelengths, particularly in the optical? The absorption columns needed in the power-law fits are low (2.6×10^{20} cm $^{-2}$, just above the Galactic column density), so the AGN is not heavily obscured. In fact, the ratio of the 2-10 keV to broad H alpha flux, which has a mean value of 40 (with large dispersion) for luminous AGNs, is 9 in IRAS 00317-2142, indicating that the AGN is *not* anomalously weak in the optical. We have every indication that IRAS 00317-2142 and the other starburst/Seyfert composite galaxies we discovered in our other programs are merely objects that exhibit normal amounts of both types of activity, which is not common in late-type galaxies. Thus, they do not form a new class of luminous X-ray sources: they are instead cleverly disguised examples of objects with which we are already well-acquainted.

Although somewhat prosaic, these results are very significant in the context of the so-called “narrow-line X-ray galaxies” which are being discovered with increasing frequency in surveys of faint *ROSAT* sources. It may well be that these too are unremarkable and are

therefore already included in current counts of Seyfert galaxies, meaning they are *not* the long-sought new component of the cosmic X-ray background. The results are scheduled for presentation at the January AAS meeting, and a journal article is nearly complete.

Our quest, however, has not been totally unfruitful as regards starburst X-ray emission. In another of the observations supported under this program, we obtained *ASCA* spectra of the southern starburst galaxy NGC 3256. This (nearly) ultraluminous infrared galaxy is a classic example of a post-merger nuclear starburst system. We found that it is the most X-ray luminous starburst yet detected. Long-slit spectroscopy and a high-resolution soft X-ray image showed that the starburst is driving a superwind which contributes $\sim 10\%$ of the soft X-ray emission. Analysis of *ASCA* spectral data led to a model with two additional X-ray components: a warm thermal plasma (~ 0.8 keV) associated with the central starburst and a hard power law component with an energy index of $\alpha \sim 0.7$. The energy budget for the two thermal components is easily explained by the mechanical energy input to the ISM from the starburst. We examined possible origins for the power law component, and concluded that neither a buried AGN, nor the expected population of High-Mass X-ray Binaries can account for the emission. However, a model in which the X-rays arise from inverse Compton scattering of the copious flux of infrared photons on the relativistic electrons produced by supernovae is consistent with the observed radio and IR fluxes and the radio and X-ray spectral indices.

This result has potentially important implications for a starburst IC contribution to the cosmic X-ray background radiation. We concluded that the faint radio source counts and spectral index distribution are consistent with a substantial fraction of the hard X-ray background arising from the starburst population. This work has recently been submitted as:

Moran, E.C., Lehnert, M.D., and Helfand, D.J. 1998 "X-rays from NGC3256: High Energy Emission in Starburst Galaxies and Their Contribution to the Cosmic X-ray Background," *Ap.J.*, submitted.

Through the Gas Darkly: An Unobscured X-ray Image of the Milky Way

This was one of the first *ASCA* projects undertaken in our program, and was intended as a pilot project to explore the feasibility of conducting a shallow but large-area survey of the Galactic Ridge emission in order to explore the origin of this mysterious component of the Milky Way, and to provide the first arcminute-resolution survey in penetrating X-rays along the Galactic equator. A dozen pointings with a few thousand seconds each were obtained and analyzed. While the thermal nature of the diffuse emission in these fields

was clear from the detected lines, and variations on one-degree scales were evident, it was clear that much longer pointings (prohibitively long for that stage of the mission) would be required to map seriously the Ridge. Furthermore, only one weak discrete source was detected. While this supported the view that the Ridge X-rays did not come from an intermediate luminosity population of discrete emitters, it did not promise great returns in terms of Galactic X-ray populations.

These data were very useful in our analysis of PV data on the supernova remnant described below, as standard background spectra are inappropriate for use in modelling thermal spectra of objects sitting on this ridge of thermal background emission. In addition, the Japanese collaborators on this project led by Prof. Koyama did continue a plane survey by investing very large amounts of time which are now beginning to yield interesting dividends on the structure of the Ridge.

The Classic Composite Supernova Remnant G29.7-0.3 (Kes 75)

The final project supported under this grant involved analysis of the public PV-phase ASCA data on the supernova remnant Kes 75. Spatial and spectral analyses of the data showed that Kes 75 is composed of a hard X-ray, nonthermal central source and a soft X-ray, thermal shell. Combining results of our analysis with radio determinations of the distance to Kes 75 and its shell diameter, we estimated the luminosities of the two components, as well as its total mass and age. The Crab-like core has an X-ray luminosity of $L_x = 1 \times 10^{36}$ ergs s⁻¹, making it the second most luminous synchrotron nebula in the Galaxy, after the Crab Nebula. The thermal shell supports an age estimate comparable to that of the Crab (1000 yrs), and the shell's inferred mass and composition are consistent with a massive progenitor. We estimated the current energy loss rate of the unseen pulsar from the synchrotron nebula's X-ray luminosity, coupled with a calculation of the total energy in nebular particles and fields from the shape of the radio-to-X-ray spectrum; this too is consistent with only 1000 yrs having elapsed since the explosion. The results were presented in full in the following publication, and were the basis on which a successful AXAF Cycle 1 proposal was written.

Blanton, E.L. and Helfand, D.J. 1996, "ASCA Observations of the Composite Supernova Remnant G29.7-0.3," *Ap.J.*, **470**, 961.

Personnel

This grant has supported several students and scientists involved in the projects discussed above.

Dr. Edward C. Moran. Ed Moran was a graduate student at Columbia when this series of grants began, and was partially supported for the final year of his graduate program with ASCA money. He then went on to a Fellowship at the Institute for Geophysics and Planetary Physics at Lawrence Livermore National Laboratory, a brief post doctoral appointment at the University of California at Berkeley, and, most recently, is one of the inaugural AXAF Fellows (also at Berkeley).

Ms. Elizabeth Blanton. Liz Blanton is in her final year of the PhD program at Columbia, and expects to defend her dissertation next spring. Before beginning her dissertation project, Liz undertook the analysis of the ASCA PV data on the composite SNR G29.7-0.3 (Kes 75) which led to the publication noted above.

Ms. Akimi Fujita. Akimi Fujita is just beginning her third year in the PhD program at Columbia. She successfully passed the qualifying examination, in part based on her first-year research project which was supported in part by this grant.

Dr. Ilana Harrus. Ilana completed her PhD in Physics at Columbia eighteen months ago. She published several papers using ASCA results including the one reporting the discovery of the X-ray synchrotron nebula surrounding the pulsar in the SNR W44, coauthored with the PI. She now holds a postdoctoral research position at the Harvard-Smithsonian Center for Astrophysics.

Dr. Hayley Richman. Hayley completed her dissertation three years ago on analysis of X-ray emission from cataclysmic variables. She is now working at Goldman-Sachs in the research department.

Mr. Don Neill. Don was supported officially as a computer applications programmer and systems manager, but became involved in some of the research. He is now planning on entering the Columbia PhD program in Astronomy in January 1999.